Assessment and Management of Atlantic and Gulf Menhaden Stocks

D. S. VAUGHAN and J. V. MERRINER

ABSTRACT—The organization of coastwide management programs for Atlantic menhaden, Brevoortia tyrannus, *and Gulf menhaden,* B. patronus, *are described. Recent assessments of the status of the Atlantic and Gulf menhaden stocks are summarized. Estimates of population size and fishing mortalities are obtained from virtual population analysis, and are used in determining spawner-recruit relationships, spawning stock ratios, yield-per-recruit, and surplus production. Management issues are addressed in the framework of assessment results.*

Introduction

Stock assessment refers to the process of collecting and analyzing biological and statistical information to determine changes in abundance of fish stocks in response to fishing, and, to the extent possible, predict future trends of stock abundance. Relevant questions arising during such an assessment include:

1) Do current landings exceed maximum sustainable yield or some other measure of optimal yield?
2) Is recruitment sufficient to support current levels of landings?
3) Does recruitment depend more on spawning stock size or more on environmental conditions?
4) Should age-at-entry to the fishery (minimum size or age landed) be raised to increase yield to the fishery?

Fishery management, or the system used to conserve and allocate fishery resources, must address these questions.

Two "overfishing" concepts are referred to in this paper. The concept of "growth overfishing" refers to the trade-off between catching greater numbers of younger and smaller fish or catching fewer numbers of older and larger fish. The trade-off depends both on the rate of growth of individual fish and on their natural mortality rate. The concept of "recruitment overfishing," on the other hand, refers to a concern that insufficient numbers of fish are reaching spawning age and subsequently reducing the number of future recruits below levels that will maintain the stock at fishable levels.

Landings and fishing effort data have been collected for the Atlantic menhaden purse-seine fishery since 1940 and for the Gulf menhaden purse-seine fishery since 1946 (Smith, 1991). Port sampling data for size and age composition from scales (procedures described by Chester, 1984) have been conducted by NMFS port samplers since 1955 for the Atlantic menhaden purse-seine reduction fishery and since 1964 for the Gulf menhaden purse-seine reduction fishery.

This paper describes the organization of coastwide management programs for the Atlantic and Gulf menhaden stocks, summarizes current information about the effects of purse-seine fishing for reduction on these stocks, and discusses management implications drawn from this information. Regular stock assessments are conducted on Atlantic and Gulf menhaden and have been presented at stock assessment workshops held by the NMFS Southeast Fisheries Science Center (Powers, 1983; Vaughan et al., 1986). Estimates of age-specific population numbers and fishing mortality rates, spawning stock, and recruits to age-1 are obtained from virtual population analysis (VPA) conducted separately for both Atlantic and Gulf menhaden. Equilibrium spawning stock ratios are computed to compare the level of spawning stock expected based on estimated fishing mortality for a fishing year to that level with no fishing mortality. Estimates of potential yield from varying age at entry to the fishery and fishing mortality rates are investigated using yield-per-recruit analysis. Recent landings are compared to estimates of maximum sustainable yield (MSY) obtained from surplus production, spawner-recruit, and population simulation models. Finally, management implications drawn from this information are discussed in light of the past decade of management actions and inactions by the coastal states.

D. S. Vaughan and J. V. Merriner are with the Beaufort Laboratory, Southeast Fisheries Science Center, National Marine Fisheries Service, NOAA, Beaufort, NC 28516.

Organization of Coastwide Management Programs

Authority for menhaden fishery management resides with individual states. The formation of the Atlantic and Gulf States Marine Fisheries Commissions (ASMFC and GSMFC, respectively) in the 1940's provided a forum for discussion and resolution of common marine resource issues and a vehicle for development of cooperative multistate fisheries programs such as for menhaden. The NMFS serves as the primary research agency dealing with menhaden for the commissions. Through the years this state-federal research and fishery management system drew heavily upon input and voluntary participation of the menhaden industry. This informal institutional arrangement provided guidance and fishery oversight through the 1960's and into the 1970's. Interstate research and monitoring coordination was through the ASMFC Advisory Committee and the GSMFC Technical Coordinating Committee (TCC).

Atlantic Menhaden

Development of an Atlantic Menhaden Management Plan under the auspices of the ASMFC and the State-Federal Fisheries Management Program was begun by the Statistical and Scientific Committee (SSC) in fall 1976. The SSC had a very general charge and prepared an interim report (plan) in February 1977. In July 1977 the SSC was asked to prepare a plan for the utilization of Atlantic menhaden that "is biologically, economically, and socially sound and which protects the resource and its users" (AMMB, 1981). Over the next 3 years the SSC and Atlantic Menhaden Management Board (AMMB) developed a plan, with supporting analyses by staff of the NMFS Beaufort Laboratory. In 1981 the AMMB, and later that year the full ASMFC, adopted the menhaden plan (AMMB, 1981). This plan recommended adjustment of time and area closures if necessary (based upon the best data available) to achieve a short-term objective of attaining an age composition in the population which included 10% age-3 or older and established an organizational framework for management. The contents of the plan and the management structure were a combined state, industry, and Federal effort of data gathering, analysis, and fishery management decision-making. Later, fishery statistical information in the fishery management plan was updated (AMMB, 1986).

In May 1982 the AMMB considered several management options which would reduce pressure on age-0 and age-1 fish and increase yield-per-recruit: Season options, closed corridor, and mesh size. The AMMB approved a variable seasonal closure by geographic area (also known as option 7) which reduced the duration of fishing activity by 4 weeks in each of four geographic areas (AMAC, 1982). Recent analyses have been conducted comparing the shortened season option to the closed corridor option (Blomo, 1987; Vaughan and Smith, 1991). That recommendation has yet to be implemented in all coastal states having an active purse-seine fishery, most notably North Carolina.

For various reasons, several states recently have passed severe limits on menhaden purse-seine fishing (New Jersey, Delaware, and South Carolina have closed all or part of their waters). Continued human population growth in the Atlantic coastal zone and conditions in the U.S. economy have resulted in pressures for fishery restrictions based on political reasons rather than the biological needs of the fishery resource as called for in the plan. This is tending toward a reduced number of operating plants and reduced fleet size in the Atlantic menhaden fishery (Smith, 1991). By 1988 reduction plants for Atlantic menhaden were reduced to four U.S. shore-based facilities (one in Maine, two in Virginia, and one in North Carolina). The 1989 fishing year was the third during which menhaden caught off Maine were transported to a land-based facility in New Brunswick, Can., for reduction, and the second year of an Internal Waters Processing venture between a Maine company and the Soviet Union; Maine fisherman caught Atlantic menhaden and offloaded the fish onto a Soviet processing vessel (F/V *Riga*). The land-based reduction plant in Maine ceased operation following the 1988 fishing year.

Furthermore, in 1987 the ASMFC in its Interstate Fishery Management Program reorganized the management structure for territorial sea fish species. That action eliminated the AMMB and AMAC; it also removed most of the industry's participation in the management process. The new plan review procedure calls for annual status reports on the fishery and resource to be done by the ASMFC Advisory Committee or a designated special plan review subcommittee (which for menhaden consisted of the former membership of AMAC).

As a result of the changes in ISMFP structure and in the reduction fishery, the ASMFC reconstituted the Atlantic Menhaden Management Board in 1988 with three state members (Maine, Virginia, and North Carolina). Two industry members were added to the Board in 1990. The Atlantic Menhaden Advisory Committee also was reconstituted to maintain the vital mix of state, industry, and Federal representation and serve as a clearinghouse for proposed regulations or laws affecting the menhaden fishery. Preparation of a major rewrite of the Fishery Management Plan by the Atlantic Menhaden Advisory Committee began in 1989 with expected completion in 1992.

Gulf Menhaden

The Gulf Menhaden Regional Fishery Management Plan (Christmas and Etzold, 1977) was developed in the 1970's as a product of the Gulf Menhaden Subcommittee of the TCC; it was composed of state, industry, and Federal representatives. The charge to the subcommittee was to consider the need for and possible procedures for establishing a uniform menhaden fishing season in the Gulf Coast states. In spring 1976 the Menhaden Subcommittee, the TCC, and the Gulf State-Federal Fishery Management Board endorsed a proposal to develop a fishery management plan for Gulf menhaden. With support of NMFS, the states, and industry, the plan was developed and issued in May 1977 (Christmas and Etzold, 1977). Revisions of the plan have been issued by the GSMFC in about 5-year intervals (Christmas et al., 1983, 1988), providing updates of stock assessments of the resource, descriptions of industry, fishery, biology, and identification and ranking of research needs. The major management feature of the Gulf menhaden plan is a uniform season (third Monday of April through the Friday following the second Tuesday in October, equals 26 weeks) adopted by all Gulf of Mexico states, with the exception of Florida, and a formal organizational structure for interjurisdictional management. Individual Gulf coast states vary in other measures (such as licenses, sanctuaries, and penalties) enforced upon the menhaden fishery. The program has been very effective and GMAC continues to meet biannually to review stock status and management measures.

Atlantic Menhaden

Summary of Recent Stock Assessments

Growth overfishing has been of pri-

Table 1.—Annual estimates of Atlantic menhaden population size (age 1-8 at start of fishing year) and numbers landed (age 1 to maximum age observed), exploitation rates (*u*, age 1-8), and weighted mean *F* (1/year), for fishing years, 1955-87.

Fishing year	Population size in billions	Numbers landed in billions	*u*	*F*
1955	6.97	2.36	0.339	0.501
1956	8.30	3.53	0.425	0.825
1957	9.83	3.21	0.327	0.819
1958	7.12	2.61	0.367	0.666
1959	17.63	5.34	0.303	0.552
1960	9.31	2.70	0.290	0.491
1961	6.84	2.60	0.380	0.706
1962	4.59	2.05	0.447	1.162
1963	3.60	1.67	0.464	1.092
1964	2.77	1.43	0.516	1.013
1965	2.59	1.26	0.486	1.040
1966	2.07	0.99	0.478	0.758
1967	2.50	0.98	0.392	0.787
1968	2.02	0.99	0.490	1.211
1969	2.22	0.71	0.320	0.676
1970	3.44	1.38	0.401	0.778
1971	2.46	0.90	0.366	0.807
1972	4.32	1.66	0.384	1.140
1973	4.18	1.79	0.428	1.755
1974	4.33	1.68	0.388	1.302
1975	5.24	1.86	0.355	1.235
1976	8.74	3.01	0.344	0.975
1977	8.40	3.19	0.380	1.011
1978	7.62	2.63	0.345	1.041
1979	7.08	2.38	0.336	0.728
1980	9.35	3.24	0.347	0.925
1981	8.15	2.80	0.344	0.763
1982	9.42	3.06	0.325	1.224
1983	6.15	2.98	0.485	1.082
1984	5.48	2.25	0.411	0.888
1985	6.85	2.39	0.349	0.990
1986	7.26	1.82	0.251	1.152
1987	8.19	2.37	0.289	0.902

mary concern with the Atlantic menhaden stock. Information presented in this section is drawn primarily from Ahrenholz et al. (1987), Vaughan and Smith (1988), and some recent analytical results prepared for AMAC. The Atlantic menhaden fishery is believed to exploit a single stock or population of fish based on tagging studies (Dryfoos et al., 1973; Nicholson, 1978a). The Atlantic menhaden fishing season runs from March 1 through the end of February of the following calendar year for the reduction fishery.

Population size (age-1 and older at the start of the fishing season) ranged from 2.0 billion Atlantic menhaden in 1968 to 17.6 billion fish in 1959 (Table 1). Population size averaged 9.2 billion menhaden between 1955 and 1961 when landings were high (averaging 604,000

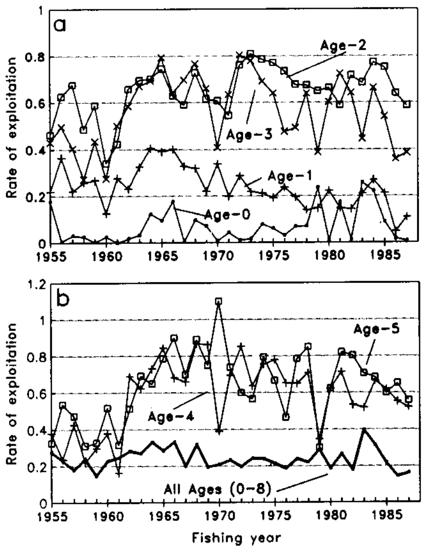

Figure 1.—Estimates of annual rates of exploitation of Atlantic menhaden (ages 0 through 5 and total population (ages 0-8)), for fishing years 1955-87.

t), and averaged 3.2 billion menhaden between 1962 and 1974 when landings were low (averaging 289,000 t). However, since 1975 population size has averaged 7.5 billion menhaden, comparing favorably to population sizes between 1955 and 1961, but landings have improved only slightly to an average of 341,000 t. The inability of the modern fishery to regain former high levels of landings is due primarily to declining mean weight at age occurring since 1970 (Reish et al., 1985; Ahrenholz et al., 1987; Vaughan and Smith, 1988), caused in part by changes in fishing patterns both geographically and seasonally. Part of this decline is due to the shift of the center of the fishing activity southward and subsequent seining on smaller fish at age and part can also be explained by the inverse relationship noted between first year growth of Atlantic menhaden and year class strength (Reish et al., 1985; Ahrenholz et al., 1987).

Short-term losses to the Atlantic menhaden stock due to the fishery can be assessed by considering the exploitation rate (Fig. 1), which is the fraction of the remaining stock removed by the fishery during some specified period of time (usually 1 year). Population exploitation rates (based on age-1 and older Atlantic menhaden) averaged 38% of the population removed by fishing for 1955 through 1987 (Table 1). From 1955 through 1961 when population size and landings were high, population exploitation rate averaged 35%. During the period of low population size and landings from 1962 through 1974, population exploitation rate averaged 43% (initially high during the mid-1960's and lower during the late 1960's and early 1970's). Since 1975 when population size and landings have improved significantly, the population exploitation rate has averaged 35%. For fishing years 1955 through 1987, an average of 24% of age-1 menhaden and 65% of age-2 and older menhaden were taken by the fishery annually, with 30% and 20%, respectively, being lost to natural causes annually (compared to 36% lost to natural causes annually in the absence of fishing mortality). Age-specific exploitation rates for age-0 menhaden range from essentially 0% to 26%.

The number of Atlantic menhaden spawners (age 3 and older at the start of the fishing year) ranged between 0.03 billion in 1973 and 1.3 billion in 1961 (Table 2). High spawning stock size (averaging 0.6 billion menhaden) was the rule between 1955 and 1961, low spawning stock size predominated between 1962 and 1974 (averaging 0.1 billion menhaden), and some improvement in spawning stock size has occurred since 1975 (averaging 0.2 billion menhaden). Between 1955 and 1961 high spawning stock size resulted in excellent recruitment of age-1 menhaden (averaging 5.5 billion) entering the fishable stock. Low spawning stock size present from 1962 through 1974 produced poor recruitment (averaging 2.2 billion menhaden). However, the somewhat improved spawning stock size present since 1975 has produced excellent recruitment (averaging 5.0 billion menhaden), comparable to that produced during the high spawning stock years (1955-61).

Since 1955 the contribution of late age-2 spawners to the spawning stock has averaged about 76% in numbers and 66% in index of egg production (Fig. 2).

Table 2.—Estimated number of spawning Atlantic menhaden (age 3-8 females) that produced the year class, estimated egg production from the spawning stock, and estimated numbers of recruits to age-1 by year class, 1955-86.

Year class	Spawners: Number in billions	Spawners: Number of eggs in trillions	Number of recruits to age-1 in billions
1955	0.795	152.6	5.68
1956	0.587	124.1	7.25
1957	0.282	65.9	3.32
1958	0.216	42.5	15.10
1959	0.538	77.2	2.22
1960	0.307	57.5	3.01
1961	1.321	152.9	2.23
1962	0.545	91.1	2.23
1963	0.176	30.3	1.74
1964	0.084	14.1	1.91
1965	0.059	9.3	1.37
1966	0.028	4.0	1.93
1967	0.056	9.4	1.18
1968	0.050	7.4	1.68
1969	0.039	6.3	2.57
1970	0.045	7.3	1.33
1971	0.084	12.6	3.44
1972	0.120	22.1	2.69
1973	0.031	5.9	2.99
1974	0.038	5.3	3.75
1975	0.044	5.9	6.80
1976	0.057	6.6	5.12
1977	0.099	10.7	4.69
1978	0.226	18.1	4.21
1979	0.199	16.3	6.65
1980	0.253	23.8	4.67
1981	0.198	17.5	6.36
1982	0.316	19.6	2.45
1983	0.178	14.4	3.81
1984	0.254	22.4	5.07
1985	0.076	8.1	4.70
1986	0.083	7.2	4.95

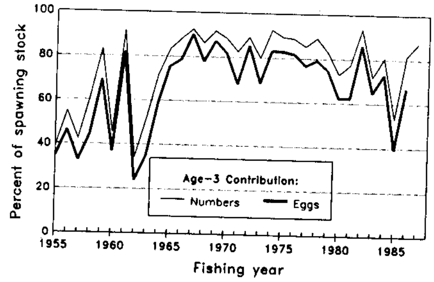

Figure 2.—Contribution of age-3 spawners to total spawning stock (numbers) and to total egg production (eggs) of Atlantic menhaden for fishing years 1955-87.

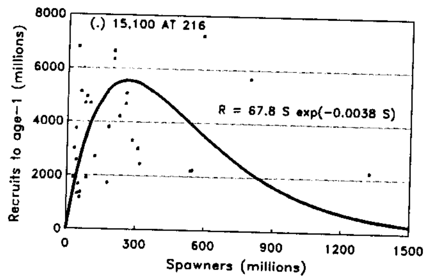

Figure 3.—Numbers of Atlantic menhaden recruits (R) plotted against numbers of spawners (S) for year classes, 1955-86. Curve represents the fitted Ricker function $R = \alpha S \exp(-\beta S)$.

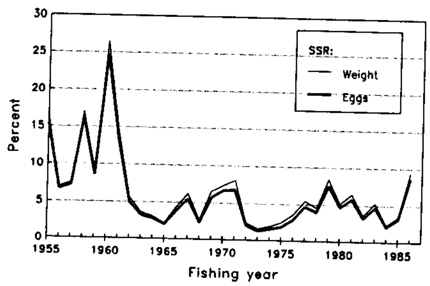

Figure 4.—Equilibrium spawning stock ratio in weight and index of egg production for Atlantic menhaden for fishing years, 1955-86.

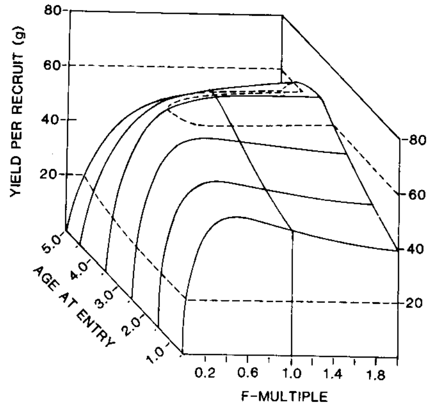

Figure 5.—Yield-per-recruit isopleth diagram for Atlantic menhaden using average growth and fishing mortality values by quarter for the 1981 fishing year.

These values were exceptionally high during the 1970's (87% and 78%, respectively), but have declined somewhat during the 1980's (77% and 65%, respectively), lessening the concern that recruitment failure in a single year class could have significant consequences on future year classes. When spawner and recruit data are fit to the Ricker model (Ricker, 1975), a statistically significant relationship is obtained (Fig. 3). However, considerable unexplained variability about the estimated spawner-recruit curve suggests that recruitment variability depends little on spawning stock size, and that environmental factors are probably more important in controlling recruitment success or failure.

Gabriel et al. (1984) suggested that a ratio of spawning stock size calculated when fishing mortality is equal to that estimated for the present divided by the spawning stock size calculated when F is equal to 0 (unfished stock). This ratio does not consider such compensatory mechanisms as increased growth rate or earlier maturity when a fish stock is reduced from fishing. It was thought that this ratio would provide values below which it should not be allowed to decline to protect the stock from recruitment overfishing. These ratios, as presented here, are calculated under the assumption of equilibrium; that is, annual age-specific estimates of F are used to project a fixed number of recruits throughout their lifespan and sum the spawning stock in weight or index of egg production. The index of egg production for Atlantic menhaden is based on the egg-length relation provided in Lewis et al. (1987).

Since 1962 the spawning stock ratio has remained below 10% (Fig. 4). Because values of 20%-40% have been used by the Gulf of Mexico and South Atlantic Fishery Management Councils in their definitions of overfishing for a number of fish stocks, these low values for Atlantic menhaden raise concern. However, periods of both poor recruitment and excellent recruitment have occurred since 1962, reinforcing the concept that environmental conditions are most important in determining recruitment success.

Yield-per-recruit models are used to determine whether Atlantic menhaden are being removed at too young an age (growth overfishing). A yield-per-recruit isopleth shows gains and losses of yield-per-recruit as a function of fishing mortality rate or age at entry to the fishery (Fig. 5). Overall yield-per-recruit for the age at entry of 0.5 year and F-multiple of 1.0 has been decreasing since 1971 with an average of 58.7 *g* for the period 1970-84 (Table 3). The proportional contribution of younger age groups to the landings has been increasing, and the average size at age (as noted earlier) is decreasing. Reduced growth and redirection of effort toward younger fish are contributing to the reduced levels in yield-per-recruit.

Recent landings of Atlantic menhaden have been increasingly dependent on age-0 menhaden (e.g., 1979, 1981, 1983, 1984, and 1985 as noted in Vaughan and Smith, 1988). Gain in yield-per-recruit from increasing age-at-entry to age-1 would have ranged from 0.7% in 1970 to 11.1% in 1979 and 8.7% in 1981. Even greater gain in yield-per-recruit could be obtained by raising the age-at-entry to age-2 (17.0% in 1979 and 12.9% in 1981). However, management options that protect only age-0 (or age-1) menhaden have been difficult to devise (Vaughan and Smith, 1991).

Historical estimates of maximum sustainable yield (MSY) range from 370,000 to 560,000 t (Schaaf and Huntsman, 1972; Schaaf, 1975, 1979; Ahrenholz et al., 1987; Vaughan and Smith, 1988). The most recent application of surplus production models conducted for AMAC, which relate landings and fishing effort, suggest estimates of MSY of 484,000 t (±87,000 t) based on landings and adjusted fishing effort data through 1986. High recruitment from 1975-1981 indicates potential yields of 416,000 to 481,000 t based on yield-per-recruit analysis. In general, estimates of MSY exceed recent landings of Atlantic menhaden which range from 238,000 to 418,600 t since 1980 with landings in 1989 at about 322,000 t.

Table 3.—Estimates of yield-per-recruit (*g*) for Atlantic menhaden for each fishing year from 1970 through 1981, and for mean conditions for the period 1970-84. Estimates are presented for three ages at entry (0.5, 1.0, and 2.0 years) and three *F*-multiples (0.4, 1.0, and 1.6) (Vaughan and Smith, 1988).

Fishing year	Age at entry			*F*-multiple		
	0.5	1.0	2.0	0.4	1.0	1.6
1970	93.6	94.3	93.8	77.1	93.6	93.5
1971	107.5	108.8	118.0	97.9	107.5	104.6
1972	102.1	103.4	118.9	108.6	102.1	94.1
1973	92.2	93.3	101.7	96.5	92.2	86.5
1974	87.2	91.1	101.6	91.8	87.2	80.0
1975	78.6	80.5	86.8	83.4	78.6	73.4
1976	66.7	68.9	78.7	65.8	66.7	60.9
1977	54.4	57.5	63.5	59.5	54.4	48.7
1978	54.1	57.0	59.8	56.4	54.1	50.3
1979	53.0	58.9	62.0	48.9	53.0	49.2
1980	53.8	54.3	61.6	54.5	53.8	49.5
1981	45.9	49.9	51.8	51.1	45.9	41.3
Mean conditions						
1970-84	58.7	60.6	64.4	57.3	58.7	55.7

Management Implications

Although landings have recovered somewhat from the depressed levels of the 1970's, they have not returned to the levels attained during the late 1950's when they averaged 625,000 t during the 1955-59 fishing years (Smith et al., 1987b). Recent estimates of MSY of 484,000 t ± 87,000 t at a mean *F* of 0.54/year were obtained from a generalized production model (1955-86); those levels are unlikely to be attained over an extended period given the present structure of the fishery. However, during the 1980's landings averaged 341,000 t with a mean *F* averaging 0.94/year suggesting greater landings would be available with less effort.

Historical MSY estimates since the early 1970's have shown no trends, ranging between 370,000 and 570,000 t. Sufficient recruitment to attain MSY has been available since 1975, but with considerable variation about the fitted spawner-recruit curves (Fig. 3). It appears that managing the fishery to maintain large numbers of spawners may prove fruitless since environmental conditions appear to outweigh the availability of spawners (as numbers or eggs) in controlling subsequent recruitment. This is suggested by a poor, but statistically significant, spawner-recruit relation and high recruitment both following and concurrent with low spawning-stock ratio. However, the Ricker spawner-recruit relationships are marginally significant, and age-3 spawners are of great importance to the spawning stock (Fig. 2). Thus, further increasing the number of older (age-3 and older) spawners would guard against a possible stock collapse brought on by heavy fishing during a period of poor recruitment.

In general, increasing the age at entry causes an increase in the yield-per-recruit, except for small *F*-multiples; e.g., *F*-multiple = 0.2 (Table 3). On the other hand, decreasing the *F*-multiple to *F*-multiple = 0.6 generally causes a decrease in yield-per-recruit, except for the 1979 fishing year. Greater declines or any increases in the *F*-multiple generally causes a decrease in yield-per-recruit at the current age at entry. These results suggest that the fishery is harvesting the Atlantic menhaden stock at too young an age, and that the age at entry should be raised to increase potential yield from the stock.

In summary, the modern purse-seine fishery for the Atlantic menhaden has a high dependency on prespawners (age-2 and younger fish), so large fluctuations in year-to-year availability and catches are to be expected. To increase yield and enhance the stability of the resource, it is desirable that the number of age classes significantly contributing to the fishery be increased. The intent is to harvest more of the stock at an older age, while decreasing fishing mortality on the younger immature menhaden. This would create a buffer in the spawning stock against future years of poor recruitment and lessen the year-to-year fluctuations in landings by increasing the proportion of Atlantic menhaden that survive to spawning age. Furthermore, greater yields would be obtained from the stock. Whether landings near the MSY estimates of 450,000 to 490,000 t are attainable is questioned because of changes in plant locations and fishing patterns. However, gains in yield-per-recruit are possible by adjusting the age at entry to the fishery (Vaughan and Smith, 1991).

Gulf Menhaden

Summary of Recent Stock Assessments

Recruitment overfishing has been of primary concern with the Gulf menhaden stock. The summary of information presented in this section draws heavily on Nelson and Ahrenholz (1986) and Vaughan (1987). The Gulf menhaden fishery is also believed to exploit a single stock or population of fish based on tagging studies (Ahrenholz, 1981). The Gulf menhaden fishing season runs from

Table 4.—Annual estimates of Gulf menhaden population size (age 1-4 at start of fishing year) and numbers landed (ages 1-4), population exploitation rate (*u*), and population *F* (1/year), for fishing years, 1964-83 (Vaughan, 1987).

Fishing year	Population size in billions	Numbers landed in billions	Population *u*	Population *F*
1964	11.32	4.95	0.437	1.071
1965	11.76	6.19	0.526	1.459
1966	7.48	4.21	0.563	1.658
1967	10.71	4.62	0.431	1.048
1968	12.07	4.51	0.374	0.850
1969	22.41	7.39	0.330	0.716
1970	17.35	5.60	0.323	0.695
1971	19.36	7.90	0.408	0.965
1972	12.44	4.87	0.392	0.910
1973	17.69	4.24	0.240	0.477
1974	20.02	5.38	0.269	0.549
1975	14.85	4.40	0.296	0.620
1976	15.27	6.17	0.404	0.951
1977	25.99	6.11	0.235	0.465
1978	36.12	9.59	0.265	0.539
1979	33.39	7.92	0.237	0.470
1980	25.01	7.15	0.286	0.593
1981	33.39	7.54	0.226	0.444
1982	39.39	9.01	0.229	0.451
1983	32.57	9.80	0.273	0.559

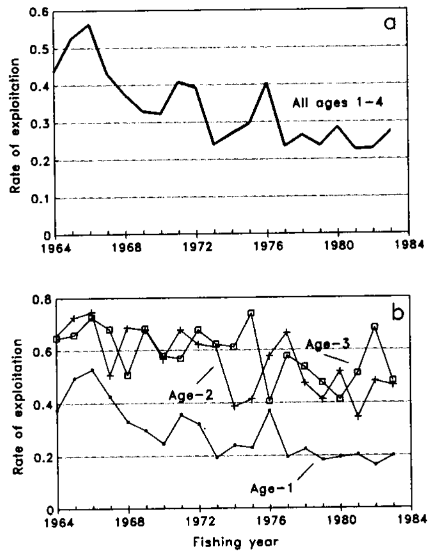

Figure 6.—Annual estimates for Gulf menhaden of (a) population exploitation rates and (b) age-specific exploitation rates (ages 1 through 3), for the period 1964-82.

Table 5.—Estimated number of spawning Gulf menhaden (age 2-4 females) that produced a year class, estimated egg production from the spawning stock, and estimated numbers of recruits to age-1 by year classes, 1964-82 (Vaughan, 1987).

Year class	Spawners[1] Numbers in billions	Spawners[1] Number of eggs in trillions	Number of recruits to age-1 in billions
1964	3.24	38.6	13.36
1965	2.13	24.4	8.26
1966	1.59	16.1	13.20
1967	0.90	10.3	13.88
1968	2.02	22.4	26.94
1969	2.56	31.6	17.46
1970	5.38	55.6	21.27
1971	4.23	54.4	12.51
1972	3.88	45.5	20.69
1973	2.60	32.9	21.21
1974	5.14	74.2	13.96
1975	5.59	88.1	16.31
1976	3.80	58.9	31.23
1977	2.98	39.4	39.81
1978	7.74	80.6	33.82
1979	10.14	125.2	23.14
1980	9.79	125.2	37.46
1981	6.50	69.2	41.79
1982	10.06	103.8	31.01

[1] Spawners (age 2 and older) present on 1 January.

mid-April through mid-October for the reduction fishery.

Population size (age-1 and older at the beginning of the fishing season in April) ranged from 7.5 billion menhaden in 1966 to 39.4 billion fish in 1981 (Table 4). Population size was low between 1964 and 1968 (averaging 10.7 billion menhaden) when landings were low (averaging 384,000 t), generally higher but more variable between 1969 and 1977 (averaging 15.5 billion menhaden) and similar with landings (averaging 547,000 t), and since 1978 generally high (averaging 33.3 billion menhaden) during a corresponding period of high landings (averaging 772,000 t). Recent landings have dropped significantly from 894,000 t in 1987, to 624,000 t in 1988 and to 570,000 t in 1989 (Smith, 1991). However, these analyses are always retrospective and have an inherent time lag. The last estimate of population size is for 1983 and more recent estimates will be included in the next stock assessment.

As with Atlantic menhaden, exploitation rates are valuable for assessing short-term losses to the Gulf menhaden stock (Fig. 6). Population exploitation rate (based on age-1 and older fish) has declined from an average of 47% between 1964 and 1968 when landings and population size were low, to an average of 32% between 1969 and 1977 when intermediate levels of landings and population size were occuring, and finally to an average of 25% since 1978 when landings and population size were large. A general decline is also noted both in the age-specific exploitation rates with fishing year. This decline in population exploitation rate, in part, represents the large increase in population size compared to relatively smaller increases in landings. Average exploitation rates (1964-83) were about 27% for age-1 Gulf menhaden and about 55% for age-2 and age-3 menhaden. Annual natural mortality averaged about 54% for age-1 Gulf menhaden and about 38% for age-2 and age-3 menhaden, although, in the absence of fishing, annual natural mortality losses would be about 67% for all ages.

Spawning is considered to peak about 1 January and coincides with the calendar year used in virtual population analysis for Gulf menhaden. Spawners (age 2 and older on 1 January) ranged between 0.9 billion Gulf menhaden in 1967 and 11.9 billion menhaden in 1983 (Table 5). Low spawning stock size was the rule from 1964 to 1968 (averaging 1.9 billion menhaden), low to moderate spawning stock size prevailed from 1969 to 1977 (averaging 4.0 billion menhaden), and generally high spawning stock size from 1978 to 1982 (averaging 9.4 billion menhaden). Recruits to age-1 on 1 January ranged from 8 billion in 1966 to 42 billion in 1982 with the three highest recruitment years for the study period (1964-82) being the 1978, 1981, and 1982 fishing years (1977, 1980, and 1981 year classes). Recruits to age-1 averaged 15.1 billion for the period 1964 through 1968, 21.6 billion for the period 1969 through 1977, and 33.4 billion since 1978. The cause for this growth in the Gulf menhaden population is unknown. The general subsidence along the Gulf of Mexico, especially along the coast of Louisiana, may provide increased nutrients for young Gulf menhaden, but Klima[1] suggests that there may be an upper limit to this enhancement phenomenon, followed by a crash in productivity.

Since 1964, the proportion of age-2 spawners to the spawning stock has been fairly consistent, ranging between 82

[1]Klima, E. 1988. In draft minutes. 39th Annu. Meet., Gulf States Mar. Fish. Comm., Ocean Springs, Miss.

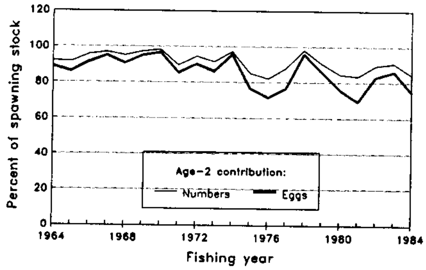

Figure 7.—Contribution of age-2 spawners to total spawning stock (numbers) and to total egg production (eggs) of Gulf menhaden for fishing years, 1964-84.

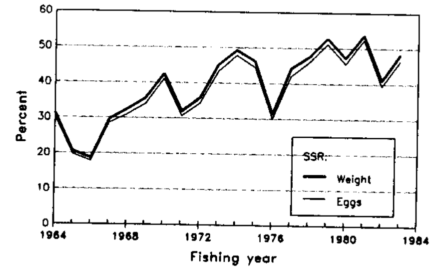

Figure 9.—Equilibrium spawning stock ratio in weight and index of egg production for Gulf menhaden for fishing years, 1955-83.

Table 6.—Estimates of yield-per-recruit (*g*) for Gulf menhaden for each fishing year from 1964 through 1983, and for two sets of mean conditions (1978-85 and 1964-85 fishing years). Estimates are presented for two ages at entry (0.5 and 1.25 years) and three *F*-multiples (0.4, 1.0, and 1.6) (Vaughan, 1987).

Fishing year	Age at entry		*F*-multiple		
	0.5	1.25	0.4	1.0	1.6
1964	17.2	17.1	11.8	17.2	19.4
1965	18.0	18.0	13.2	18.0	19.7
1966	18.6	18.6	14.1	18.6	20.3
1967	17.0	17.0	11.1	17.0	19.3
1968	17.3	17.3	12.5	17.3	19.3
1969	10.4	10.4	5.8	10.4	13.4
1970	15.3	15.3	9.6	15.3	18.1
1971	17.5	17.5	12.4	17.5	19.5
1972	15.7	15.7	11.1	15.7	17.3
1973	15.1	15.1	10.2	15.1	17.5
1974	16.3	16.3	9.6	16.3	19.8
1975	16.5	16.5	10.9	16.5	19.2
1976	18.6	18.6	11.9	18.6	21.1
1977	19.3	19.3	13.2	19.3	21.4
1978	14.0	14.0	8.3	14.0	16.8
1979	13.4	13.4	8.3	13.4	16.2
1980	15.4	15.4	9.3	15.4	18.3
1981	10.2	10.2	5.8	10.2	12.4
1982	6.9	6.9	3.9	6.9	9.2
1983	13.6	13.6	8.5	13.6	16.1
	---------- Mean conditions ----------				
1978-85	12.2	12.2	7.9	12.2	14.2
1964-85	15.8	15.8	10.6	15.8	18.1

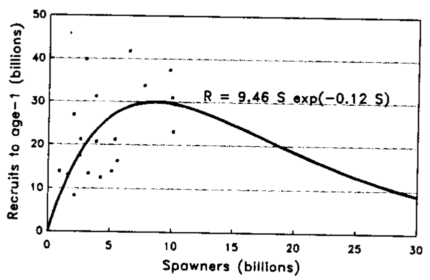

Figure 8.—Numbers of Gulf menhaden recruits (R) plotted against numbers of spawners (S) for year classes, 1964-82. Curve represents the fitted Ricker function $R = \alpha S \exp(-\beta S)$.

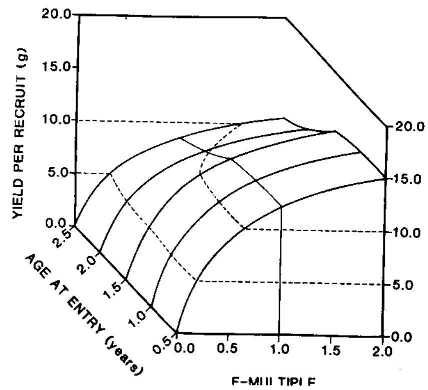

Figure 10.—Yield-per-recruit isopleth diagram for Gulf menhaden using average conditions of growth and fishing mortality for the period 1978-85.

and 98% in numbers (Fig. 7). Since the mid-1970's, the contribution of age-2 spawners to the spawning stock has averaged about 88% in numbers. As with Atlantic menhaden, after fitting the Ricker curve to Gulf menhaden spawner and recruit data, considerable unexplained variability remains due to environmental conditions or measurement error (Fig. 8). Again, these relationships are statistically significant, so that future recruits do depend to some extent on the size of the spawning stock which produced them, but the large scatter suggests that environmental factors are probably more important in controlling recruitment success or failure.

Contrary to the equilibrium spawning stock ratios obtained annually for Atlantic menhaden, those obtained annually for Gulf menhaden (both biomass and index of egg production) have been generally much larger (20-50%) and with an upward trend (Fig. 9). The index of egg production for Gulf menhaden is based on the egg-length relationship provided in Lewis and Roithmayr (1981). The lowest values were obtained from estimated fishing mortality rates from the 1965 and 1966 fishing years, the highest values were obtained from estimated fishing mortality rates from the 1981 fishing year. These results are not surprising given the decline in F shown in Figure 5, both for all ages 1-4 and especially for age-1. However, with the high natural mortality ($M = 1.1$) for Gulf menhaden and short lifespan (about 4 years), a sudden turnaround in recruitment could still present problems to the fishery.

A yield-per-recruit isopleth shows gains and losses of yield-per-recruit as a function of fishing mortality rate or age-at-entry to the fishery (Fig. 10). Overall yield-per-recruit of Gulf menhaden, for the age at entry of 1.25 years (or 0.5 year) and F-multiple of 1.0 has shown no trend since 1964 with an average of 15.8 g for the period 1964-85 and an average of 12.2 g for the period 1978-85 (Table 6). Yield-per-recruit could actually be increased with higher rates of fishing, as maximum biomass is obtained at age 1.5 years and the rate of natural mortality is quite high. However, attempts to increase yield-per-recruit could have severe consequences: Results from population simulation studies by Nelson and Ahrenholz (1986) and Vaughan (1987) indicate that recruitment overfishing is likely to occur at F-multiples greater than 1.5 for 1978-85 mean conditions.

Estimates of MSY from surplus production models continue the upward trend noted in Vaughan et al. (1986). Chapoton (1972) obtained an estimate of MSY of 430,000 t for the 1946-70 period, Schaaf (1975) obtained an estimate of 478,000 t for the 1946-72 period, Nelson and Ahrenholz (1986) obtained estimates ranging from 540,000 to 640,000 t for the 1946-79 period, and more recently Vaughan (1987) obtained estimates ranging from 620,000 to 825,000 t. The primary biological concern raised by stock assessment scientists is that the nature of the descending limb on the surplus production model can only be determined accurately if landings exceed the current MSY for several years. If the descending limb were steep, heavy fishing could put the stock at greater risk. The Pella and Tomlinson (1969) model, estimated from Gulf menhaden catch and effective effort data, has a flat descending limb (Vaughan, 1987).

Estimates of MSY range from 620,000 to 700,000 t based on surplus production models (landings and fishing effort data from 1946-85 fishing years), and from 705,000 to 825,000 t based on population simulation models (using Ricker spawner-recruit relationships based on 1964-82 year classes) (Vaughan, 1987). The latter range of estimates for MSY is probably more indicative of the average landings that could have been removed from the Gulf menhaden stock during the period from which data were obtained (1964-85 fishing years), given the limitations in adjusting the fishing effort (restricted to 1964-83 fishing years) used in surplus production models and the firmer biological basis for the population simulation approach. Our major concern was that the high landings greater than 800,000 t during most of the 1980's may have been too high.

Management Implications

Both landings and fishing effort have increased dramatically since 1946 (Smith et al., 1987a), with record landings during the 1984 fishing season (982,000 t) and record high nominal fishing effort during the 1983 fishing season (655,800 vessel-ton-weeks). Recruitment to age-1 (on 1 January) varied between 8.3 and 41.8 billion fish (Table 5). Many of the higher values have occurred since 1977, producing greater values for population size and numbers of spawners (Tables 4, 5) and smaller values for exploitation rate (Table 4) in the last decade. Therefore, effective fishing effort has actually declined since the 1960's (Vaughan, 1987). The implication is that the increased landings since 1978 are the result of exceptionally good recruitment (i.e., year classes) and not increased effective fishing effort. Increased geographic availability of Gulf menhaden to the fishery does not seem likely given the closure of reduction plants at the geographic extremes (Nicholson, 1978b), and area and seasonal closures that have been implemented (Christmas and Etzold, 1977; Christmas et al., 1983, 1988).

Historical estimates of maximum sustainable yield (MSY) range from 430,000 to 585,000 t (Chapoton, 1972; Schaaf, 1975; Nelson and Ahrenholz, 1986). With data through the 1984 fishing year, surplus production models produced estimates of MSY from 620,000 to 700,000 t (Vaughan, 1987). Recent recruitment (1976-82) has been excellent and indicates potential yields of about 718,000 t based on a yield-per-recruit analysis. Employing population simulation models with a spawner-recruit relation produced estimates of MSY ranging from 705,000 to 825,000 t. In general, MSY has been exceeded by recent Gulf menhaden landings ranging from 552,600 to 982,800 t during the 1980's. Landings since 1987 have dropped below 800,000 t to 570,000 t in 1989.

The Gulf menhaden is short-lived and has a higher natural mortality than the Atlantic menhaden. Both estimated spawning stock size (Table 5) and spawning stock ratio (Fig. 10) appear healthy, but a rapid change in favorable conditions could alter this picture rapidly, so caution is advised relative to the high *F*'s found and the dependency of the fishery upon very few age groups. Hence, expansion of this fishery by effort or area is not recommended. Concern is therefore raised with the operation of a new reduction plant in 1989 adjacent to a defunct site near Morgan City, La., and expansion of the fishing season for bait fisheries in Florida and Louisiana.

In summary, the Gulf menhaden fishery is currently fully exploited and appears reasonably stable biologically in view of the age composition, life span, and effects of environmental factors. Annual production, fishing effort, and fleet size appear reasonably balanced. Although recent harvests have declined rapidly (from 894,000 t in 1987 to 570,000 t in 1989, it was not considered likely that the high landings (above MSY) obtained during the 1980's could be maintained indefinitely. Landings on the order of 600,000 t are probably more realistic as a long-term average.

Summary

In conclusion, management programs are in place for both Atlantic and Gulf menhaden stocks through the Atlantic and Gulf States Marine Fisheries Commissions. Cooperation is ongoing and seems to work on the Gulf of Mexico Coast, but the Atlantic menhaden plan is not fully implemented. Reevaluation of the management options for the Atlantic menhaden reduction fishery is underway and may replace the variable season closure management recommendation. The expansion of fishing on the spawning stock in New England waters concurrently with increasing fishing pressure on prespawning menhaden off Virginia and North Carolina in the fall prompts concern for maintenance of the Atlantic menhaden resource.

Acknowledgments

Thanks are due to the many past and present employees of the Beaufort Laboratory, Southeast Fisheries Science Center, NMFS, NOAA, who were involved in the many aspects of the menhaden program, especially Dean W. Ahrenholz, Donnie L. Dudley, Ethel A. Hall, Eldon J. Levi, and Joseph W. Smith. We are grateful to Charles W. Krouse for his assistance in preparing the computerized data sets for analysis and for other programming help. We would also like to thank Dean W. Ahrenholz and Joseph W. Smith, for their many helpful comments, and Herbert R. Gordy and Curtis W. Lewis for drafting of figures.

Literature Cited

Ahrenholz, D. W. 1981. Recruitment and exploitation of Gulf menhaden, *Brevoortia patronus*. Fish. Bull. 79:325-335.

________, W. R. Nelson, and S. P. Epperly. 1987. Population and fishery characteristics of Atlantic menhaden, *Brevoortia tyrannus*. Fish. Bull. 85:569-600.

AMAC. 1982. Status and management recommendations for the purse-seine fishery, report to the Atlantic Menhaden Implementation Subcommittee (AMIS). Atl. Menhaden Advis. Committee, Atl. States Mar. Fish. Comm., Wash., D.C., 15 p.

AMMB. 1981. Fishery management plan for Atlantic menhaden, *Brevoortia tyrannus* (Latrobe). Atl. Menhaden Manage. Board, Atl. States Mar. Fish. Comm., Wash., D.C., Fish. Manage. Rep. 2, 134 p.

________. 1986. 1986 supplement to Atlantic menhaden fishery management plan. Atl. Menhaden Manage. Board, Atl. States Mar. Fish. Comm., Wash., D.C., Fish. Manage. Rep. 8, 61 p.

Blomo, V. J. 1987. Distribution of economic impacts from proposed conservation measures in the U.S. Atlantic menhaden fishery. Fish. Res. 5:23-38.

Chapoton, R. B. 1972. The future of the Gulf menhaden, the United States' largest fishery. Proc. Gulf Caribb. Fish. Inst. 24:134-143.

Chester, A. J. 1984. Sampling statistics in the Atlantic menhaden fishery. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 9, 16 p.

Christmas, J. Y., and D. J. Etzold. 1977. The menhaden fishery of the Gulf of Mexico, United States: A regional management plan. Gulf Coast Res. Lab. Tech. Rep. Ser. 1, 53 p.

________, ________, and L. B. Simpson. 1983. The menhaden fishery of the Gulf of Mexico, United States: A regional management plan. Gulf States Mar. Fish. Comm., Rep. 8, 107 p.

________, ________, ________, and S. Meyers. 1988. The menhaden fishery of the Gulf of Mexico, United States: A regional management plan. Gulf States Mar. Fish. Comm., Rep. 18, 135 p.

Dryfoos, R. L., R. P. Cheek, and R. L. Kroger. 1973. Preliminary analysis of Atlantic menhaden, *Brevoortia tyrannus*, migrations, population structure, survival and exploitation rates, and availability as indicated from tag returns. Fish. Bull. 71:719-734.

Gabriel, W. L., W. J. Overholtz, S. A. Murawski, and R. K. Mayo. 1984. Spawning stock biomass per recruit analysis for seven Northwest Atlantic demersal finfish species. NMFS Woods Hole Lab. Ref. Doc. 84-23, 36 p.

Lewis, R. M., D. W. Ahrenholz, and S. P. Epperly. 1987. Fecundity of the Atlantic menhaden, *Brevoortia tyrannus*. Estuaries 10:347-350.

________ and C. M. Roithmayr. 1981. Spawning and sexual maturity of Gulf menhaden, *Brevoortia patronus*. Fish. Bull. 78:947-951.

Nelson, W. R., and D. W. Ahrenholz. 1986. Population and fishery characteristics of Gulf menhaden, *Brevoortia patronus*. Fish. Bull. 84:311-325.

________, M. C. Ingham, and W. E. Schaaf. 1977. Larval transport and year-class strength of Atlantic menhaden, *Brevoortia tyrannus*. Fish. Bull. 75:23-41.

Nicholson, W. R. 1978a. Movements and population structure of Atlantic menhaden indicated by tag returns. Estuaries 1:141-150.

________. 1978b. Gulf menhaden, *Brevoortia patronus*, purse seine fishery: Catch, fishing activity, and age and size composition, 1964-73. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF 722, 9 p.

Pella, J. J., and P. K. Tomlinson. 1969. A generalized stock production model. Int.-Am. Trop. Tuna Comm. Bull. 14:420-496.

Powers, J. E. 1983. Report of the Southeast Fisheries Center Stock Assessment Workshop, August 3-6, 1982. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-SEFC-127, 229 p.

Reish, R. L., R. B. Deriso, D. Ruppert, and R. J. Carroll. 1985. An investigation of the population dynamics of Atlantic menhaden (*Brevoortia tyrannus*). Can. J. Fish. Aquat. Sci. 42:147-157.

Ricker, W. E. 1954. Stock and recruitment. J. Fish. Res. Board Can. 11:559-623.

________. 1975. Computation and interpretation of biological statistics of fish populations. Bull. Fish. Res. Board Can. 191, 382 p.

Schaaf, W. E. 1975. Status of the Gulf and Atlantic menhaden fisheries and implications for resource management. Mar. Fish. Rev. 37(9):1-9.

________. 1979. An analysis of the dynamic response of Atlantic menhaden, *Brevoortia tyrannus*, to an intensive fishery. Rapp. P.-v. Reun. Cons. Int. Explor. Mer 177:243-251.

________ and G. R. Huntman. 1972. Effects of fishing on the Atlantic menhaden stock: 1955-1969. Trans. Am. Fish. Soc. 101:290-297.

Smith, J. W. 1991. The Atlantic and Gulf menhaden purse seine fisheries: Origins, harvesting technologies, biostatistical monitoring, recent trends in fisheries statistics, and forecasting. Mar. Fish. Rev. 53(4):28-39.

________, E. J. Levi, D. S. Vaughan, and E. A. Hall. 1987a. The Gulf menhaden, *Brevoortia patronus*, purse seine fishery, 1974-1985, with a brief discussion of the age and size composition of the landings. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 60, 8 p.

________, W. R. Nicholson, D. S. Vaughan, D. L. Dudley, and E. A. Hall. 1987b. The Atlantic menhaden, *Brevoortia tyrannus*, purse-seine fishery, 1972-1984, with a brief discussion of the age and size composition of landings. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 59, 23 p.

Vaughan, D. S. 1987. A stock assessment of the Gulf menhaden, *Brevoortia patronus*, fishery. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 58, 18 p.

________, J. V. Merriner, D. W. Ahrenholz, and R. B. Chapoton. 1986. Stock assessment of menhaden and coastal herrings. U.S. Dep. Commer., NOAA Tech. Memo. NMFS-SEFC-178, 46 p.

________ and J. W. Smith. 1988. A stock assessment of the Atlantic menhaden, *Brevoortia tyrannus*, fishery. U.S. Dep. Commer., NOAA Tech. Rep. NMFS 63, 18 p.

________ and ________. 1991. Biological analysis of two management options for the Atlantic menhaden fishery. Mar. Fish. Rev. 53(4): 56-64.